2D/3D Quench Simulation using ANSYS for Epoxy Impregnated Nb_3Sn High Field Magnets

Ryuji Yamada, Eric Marscin, Ang Lee, Masayoshi Wake, and Jean-Michel Rey

***Abstract*— A quench program using ANSYS is developed for the high field collider magnet for three-dimensional analysis. Its computational procedure is explained. The quench program is applied to a one meter Nb_3Sn high field model magnet, which is epoxy impregnated. The quench simulation program is used to estimate the temperature and mechanical stress inside the coil as well as over the whole magnet. It is concluded that for the one meter magnet with the presented cross section and configuration, the thermal effects due to the quench is tolerable. But we need much more quench study and improvements in the design for longer magnets.**

***Index Terms*— Quench Program, ANSYS, Stress Distribution.**

I. Introduction

Each LHC magnet made of NbTi is provided with a high current diode for dissipating individual magnet's stored energy into its own cold mass for its quench protection. It is reported the magnet temperature rise is in the order of 300 to 350 K in the event of an individual quench [1]. The Rutherford cable of the LHC magnet is made of NbTi superconducting strands, wrapped with polyimide, but not epoxy impregnated. Therefore, the individual conductor cable or individual conductor block has freedom to expand in some extent during a quench. After the quench, when the conductor is cooled back, the cable will return close to the original position.

For the design of the high field collider magnets beyond 10 Tesla, Nb_3Sn material is used. The Nb_3Sn strand becomes brittle after its heat treatment. Therefore, a coil wound with Nb_3Sn Rutherford cable has to be completely epoxy impregnated to keep the conductor rigidity. To accomplish this, the coil is epoxy impregnated together with spacing wedges and other material. When the superconductor quenches, either spontaneously or with heaters, the superconductor cable is rapidly heated up, but the surrounding material will not be heated up, except by the eddy current in them due to the rapidly changing magnetic field. The quenched conductor is locally heated up to 100 K to 300 K, depending on the condition, while the surrounding material is almost kept at cold temperature. The stored energy of the magnet is becoming quite high, so it has to be dumped quickly into the magnet coil itself for safe operation. We have to make sure not to cause any excessive damage to the epoxied structure during this time. The quench will cause shear forces between the cable and the insulation layer, and possibly cause cracking in the insulation. This will be a cause of training of the magnet. This problem becomes drastically important with longer magnets, as studied and reported in our previous papers [2, 3]. We have to investigate what is a safe margin for a high field accelerator magnet made with Nb_3Sn strands.

In the present study, we developed a more precise quench program using ANSYS, and studied the thermal and resulting mechanical stress in the magnets after a quench. In the 2-dimensional magnet cross section, this will cause the compression in every part of the coil, especially in the heated conductors and in the wrapping insulation material. Also, this will cause shear forces between the heated conductor and the surrounding material through the insulation material. In 3-dimensions, the superconductor will also expand longitudinally, causing longitudinal shear stress with the surrounding material.

II. Simulation Calculation

In this paper we study the thermal and mechanical effects after a quench has started using the geometry of the dipole magnet with a cosine theta design, which is being developed at Fermilab [4]. Its regular ANSYS analysis has been done and reported for its structural analysis and for magnetic force analysis [5]. We use the same geometry, but with more detailed meshes around the conductor area and a separate insulation layer around the conductors to study the effect on the insulation layer.

During a quench, electrical and thermal effects occur simultaneously. However, because the electrical changes occur much more quickly than the thermal changes, we assume in this paper that the thermal effects due to a quench can be handled independently to a good approximation. Electrical effects will be added in a future study.

The parameters of the magnet, including the averaged magnetic field value at each conductor cable at the nominal current value, are stored in the ANSYS program. The real heaters are installed on the outside surface of the outer layer of the coil. The response time of these heaters is studied with a separate, simpler ANSYS program, and found to have a delay time of 30 ms.

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III. 2D SIMULATION CALCULATION FOR ONE METER MAGNET

The simulation is a combination of both ANSYS solver routines for temperature analysis and the ANSYS script language for computational purposes. The flow chart of the simulation is shown in Fig.1. It basically simulates a quench in a 2D representation of a quarter of the magnet. The temperature simulation takes about 20-30 minutes to run with a 1ms time step for 100 ms on a 2.2 GHz processor with 1 GB of RAM, while the stress simulation requires 30 minutes [6].

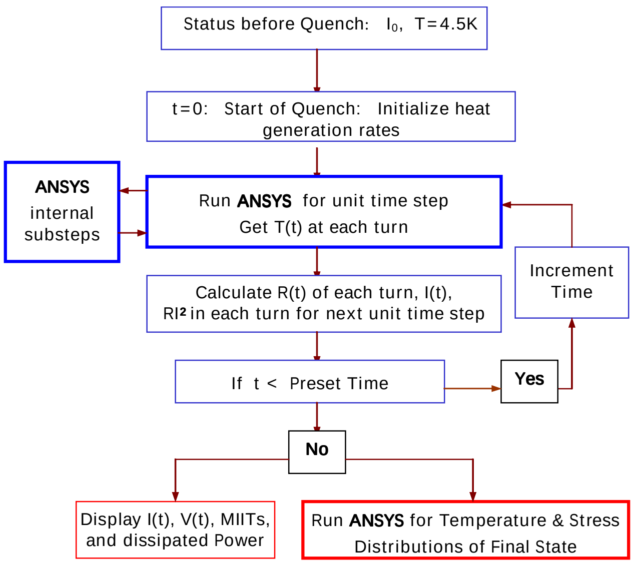


Fig.1. Flow chart of ANSYS Quench Simulation

First, the whole magnet system is initialized to the original temperature of 4.5 K, and the initial current of I_0. All turns initially generate no heat, but the quenching turn receives 0.0065 J to initiate the quench.

Next, the program runs the ANSYS solver to compute the temperature distribution at the end of the given time step due to the given amount of heat generation. By changing the time step, we found 1 ms is adequate for our calculation. This simulation is done with a standard transient thermal analysis within ANSYS. While the simulation runs for a 1 ms time step, ANSYS will use smaller sub steps during the solution portions of the program, if the thermal changes within the simulation are too severe to be calculated at a 1 ms time step. At these sub steps, the thermal properties of the materials are updated to reflect the new temperatures, but resistance, current, and heat generation is not updated. Upon completion of the solution, the program extracts the temperature at three points on each conductor cross section, and then averages the recorded temperatures together to get a temperature value to use in calculations.

Once that is complete, the resistance across the coil is calculated utilizing the newly found temperatures and the parameter list of the magnet. This calculation assumes that the entire turn has the same temperature and resistance.

The new current is then calculated from the inductance of the magnet, the total resistance, and the dump resistor. This value and the calculated resistances are then used to determine the amount of power that will be emitted by each turn for the next 1 ms. Once the power is determined, the simulation repeats again by solving for the temperature using the new heat generation values. The simulation repeats until it has simulated up to 100 ms. The temperature distribution around the coil is shown in Fig. 2, which is calculated with a dump resistor of 30 mΩ.

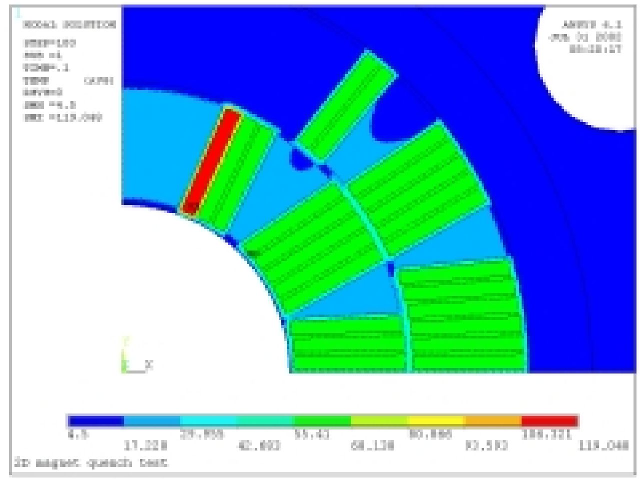


Fig.2. 2D temperature distribution at 100 ms. The quench started in the leftmost conductor, which has the highest temperature of 119°K.

A quench is detected in the simulation when there is a voltage of 0.01V across the coil. The heater is activated 30 ms after this time. The heater adds a set amount of heat to each turn that is affected by a heater to simulate the temperature rise. The heater can also be simulated in its actual location on the magnet, although that is not shown in these diagrams.

At each 1 ms time step, values such as the I(t), V(t), the MIITs values of the quench starting point, and the values of the dumped energy into the coil and the dump resistor are recorded and stored as a function of time. These values can be plotted in graphs at the end of the run.

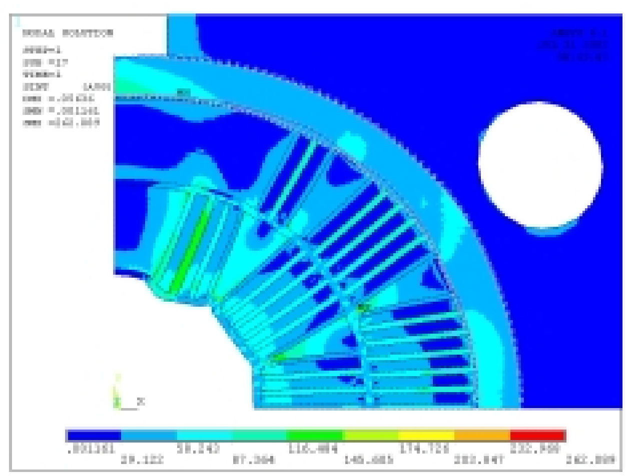


Fig.3. 2D stress intensity distribution at 100 ms. The stress is highly localized around the leftmost conductor, where the quench started. The stress beyond 175 MP is seen only at the tips of wedges.

Once the temperature simulation is complete, the stress analysis of the magnet is done with ANSYS, as shown in Fig 3. The result shows that the insulation material may be exposed to up to 140 MP around the quenching conductor.

In this two-dimensional analysis, the heat conduction in the cable direction is neglected. Therefore, the resulting temperature and stress value may be overestimated.

IV. 3D Simulation for One Meter Magnet

The three dimensional model of the magnet is made by extruding the two dimensional cross-section of the magnet to the distance required by the magnet. Therefore, the real magnet end parts are not reproduced. The one-meter magnet is segmented into 15 parts, as is shown in Fig.4, along the main axis of the magnet. There are about 66,000 elements in the ANSYS simulation. The calculation time for this model is about 8 hours for temperature simulation and 30 hours for stress simulation with a time step of 1 ms for 100 ms using a 2.2 GHz Pentium 4 computer with 1 GB of memory.

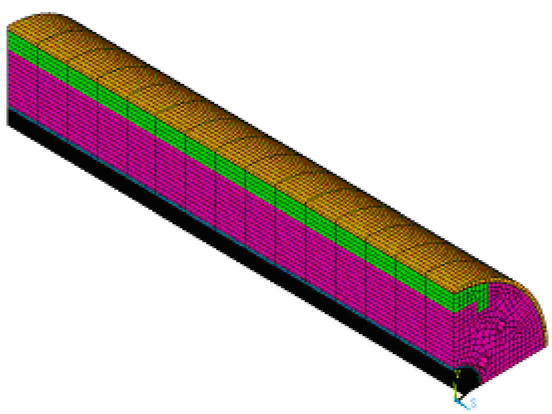


Fig. 4. Mesh division of a quadrant of one-meter long magnet.

The procedure for this case is almost the same as that in the 2-D case except that there are multiple temperature, resistance, and heat values along the same turn. The quenching energy is applied to the middle segment of the quenching turn. Like in the 2D model, the dump resistor of 30 mΩ is used in this case.

V. 3D Temperature Analysis

The heat generated in every conductor turn is calculated every millisecond, and its data is used by the ANSYS program to calculate the temperature every ms in every turn. The temperature rise with time was animated using the ANSYS results. This animation allows the visual confirmation of heat transfer characteristics very vividly. The quenching conductor cables are heated far more than the surrounding material and non-quenching conductors.

A typical spontaneous quench at the center of one-meter magnet is studied. Fig.5 shows the temperature distribution in the center plane of the one-meter magnet at 100 ms. The cable at the highest field point that starts the quench is heated up to 113 K, and the next neighboring cable is heated up to 62 K. The remaining conductor cables, which are heated by heaters at 30 ms after the quench detection, go up to 60 K. Because of the short time constant system of 67 ms, the main current in the cables decays fast, not generating too much heat in the main part of the coil. The temperature of the wedges is about 20 K at 100 ms.

In comparison with 2D case of Fig. 2, it is shown the maximum temperature is slightly lower as expected. From this data, we can judge that this is due to heat transfer in longitudinal direction.

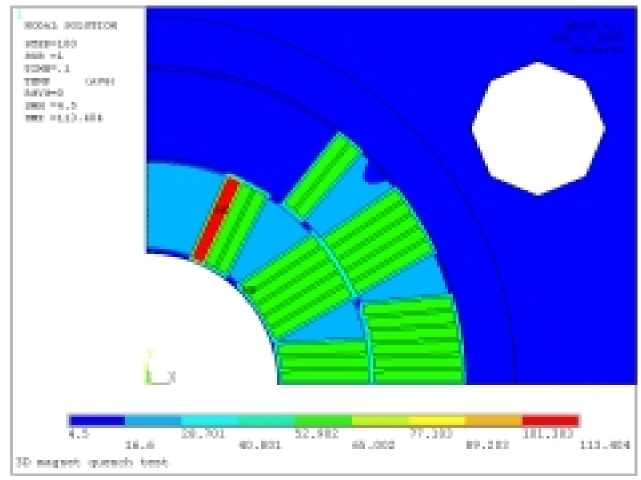
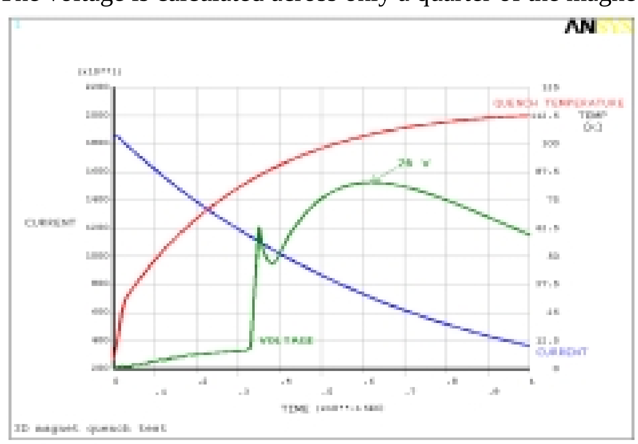


Fig.5. Temperature distribution in the center plane of one-meter magnet at 100 ms with 3D analysis. The quench started in the leftmost conductor, which has the highest temperature of 113°K.

VI. Parameter Variation

Temperature of the quench starting point, the magnet current and magnet voltage of the model, during quenching time are shown in Fig.6. The data points are derived during the thermal analysis at every 1 ms, and then stored in the computer.

The quench is detected at 1 ms, which is shown by the constant current until 1 ms has passed. The voltage jump shown at around 30 ms is due to the heater being activated. The voltage is calculated across only a quarter of the magnet.



Fig, 6. T(t) of the quenching point, I(t),V(t) of 3D magnet. The current is decaying exponentially, while the temperature of the quench starting point is increasing smoothly. The voltage increase at 33 ms is due to the heater being activated, and it peaks at 26 V.

VII. 3D STRESS ANALYSIS

Before the quench, the coil is prestressed longitudinally. During the quench the coil expands longitudinally and radially due to the thermal expansion, while being constrained at both ends by the outside stainless steel skin at 4.5 K. For the 3-dimensional stress analysis, the longitudinal boundary condition is set so that both ends are kept rigid, which is realized by the symmetry condition.

The stress intensity distribution in the central cross section, where the quench started is shown in Fig. 7. It is similar to that obtained in 2-dimensional case as shown in Fig.3. The maximum stress intensity in the insulation is about 150 MP.

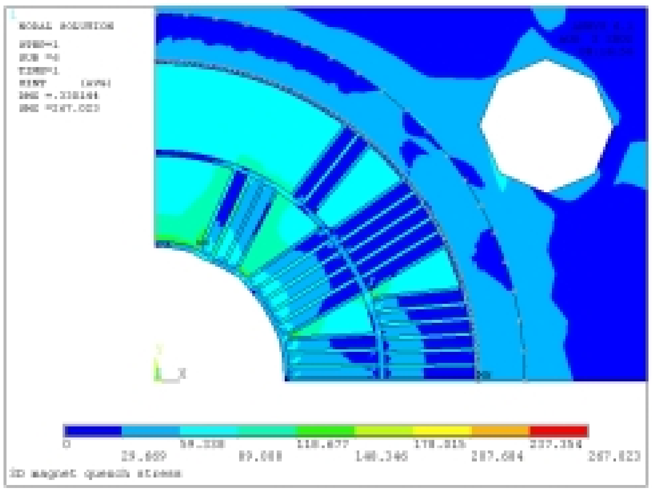


Fig. 7. 3D stress intensity distribution at 100 ms, in the center cross sectional plane, where the quench started. The stress is localized around leftmost turns. Stress beyond 178 MP is localized at the tips of wedges.

The axial stress in the conductor turns along the magnet is shown in Fig.8. The quenching conductor turn is stressed most at 68MP, while other conductor turns are at 25 MP.

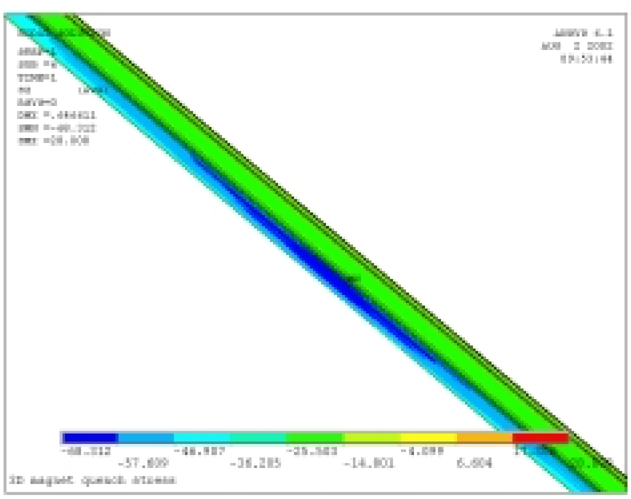


Fig. 8. 3D stress in the z-direction at 100 ms. The maximum axial stress is at the center of the innermost conductor, where the quench started. The center point has the highest compression at –68 MP.

VIII. CONCLUSION

We have explained a new two and three dimensional simulation method using ANSYS to estimate the thermal and its resulting mechanical stress distribution in the magnet after quench, especially in the conductor and insulation material. It will work well as a new quench research program, and will provide much more accurate information about the magnet quench process because it incorporates all components of the magnet for the quench calculation.

This simulation incorporates the heater system for magnet quench protection. Together with the use of the quench starting mechanism, we can study the details of quench propagation mechanism by changing the variable parameters in the simulation. In the voltage shape we can observe the propagation of quench into the neighboring conductor turns.

By comparing the data from the 2D and 3D thermal and stress analysis, it appears that the 2D analysis represents the 3D analysis quite well, and gives reasonable upper limits for the temperature and stress data.

In a one-meter magnet with an adequate dump resistor, the temperature rise and the thermal stress may be acceptable, but with longer magnets, much more study is needed. The situation seems very serious with a longer magnet.

At present this simulation program does not include the detailed magnet end structure, the effects of eddy current, quenchback, or Lorentz force. These will be implemented in a future version of the program. The present system is already applicable for many detailed studies, but with enhancement of further addition, it will be very powerful quench simulation tool.

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